

TEMPERATURE

CRITERIA:

Freshwater Aquatic Life

For any time of year, there are two upper limiting temperatures for a location (based on the important sensitive species found there at that time):

1. One limit consists of a maximum temperature for short exposures that is time dependent and is given by the species-specific equation:

$$\text{Temperature } (C_0) = (1/b) (\log_{10} [\text{time (min)}] - a) - 2_0 \text{ C}$$

where: \log_{10} = logarithm to base 10 (common logarithm)

a = intercept on the "y" or logarithmic axis of the line fitted to experimental data and which is available for some species from Appendix II-C, National Academy of Sciences 1974 document.

b = slope of the line fitted to experimental data and available for some species from Appendix II-C, of the National Academy of Sciences document.

and

2. The second value is a limit on the weekly average temperature that:

- a. In the cooler months (mid-October to mid-April in the north and December to February in the south) will protect against mortality of important species if the elevated plume temperature is suddenly dropped to the ambient temperature, with the limit being the

acclimation temperature minus 2 Pto c when the lower lethal threshold temperature equals the ambient water temperature (in some regions this limitation may also be applicable in summer).

or

- b. In the warmer months (April through October in the north and March through November in the south) is determined by adding to the physiological optimum temperature (usually for growth) a factor calculated as one-third of the difference between the ultimate upper incipient lethal temperature and the optimum temperature for the most sensitive important species (and appropriate life state) that normally is found at that location and time.

or

- c. During reproductive seasons (generally April through June and September through October in the north and March through May and October through November in the south) the limit is that temperature that meets site-specific requirements for successful migration, spawning, egg incubation, fry rearing, and other reproductive functions of important species. These local requirements should supersede all other requirements when they are applicable.

or

- d. There is a site-specific limit that is found necessary to preserve normal species diversity or prevent appearance of nuisance organisms.

Marine Aquatic Life

In order to assure protection of the characteristic indigenous marine community of a water body segment from adverse thermal effects:

- a. the maximum acceptable increase in the weekly average temperature resulting from artificial sources is 1° C (1.8 F) during all seasons of the year, providing the summer maxima are not exceeded; and
- b. daily temperature cycles characteristic of the water body segment should not be altered in either amplitude or frequency.

Summer thermal maxima, which define the upper thermal limits for the communities of the discharge area, should be established on a site-specific basis. Existing studies suggest the following regional limits:

	Short-term Maximum	Maximum True Daily Mean*
Sub tropical regions (south of Cape Canaveral and Tampa Bay, Florida, and Hawaii	32.2° C (90° F)	29.4° C (85° F)
Cape Hatteras, N.C., to Cape Canaveral, Fla.	32.2° C (90° F)	29.4° C (85° F)
Long Island (south shore) to Cape Hatteras, N.C.	30.6° C (87° F)	27.8° C (82° F)

(* True Daily Mean = average of 24 hourly temperature readings.)

Baseline thermal conditions should be measured at a site where there is no unnatural thermal addition from any source, which is in reasonable proximity to the thermal discharge (within 5 miles) and which has similar hydrography to that of the receiving waters at the discharge.

INTRODUCTION:

The uses of water by man in and out of its natural situs in the environment are affected by its temperature. Offstream domestic uses and instream recreation are both partially temperature dependent. Likewise, the life associated with the aquatic environment in any location has its species composition and activity regulated by water temperature. Since essentially all of these organisms are so-called "cold blooded" or poikilotherms, the temperature of the water regulates their metabolism and ability to survive and reproduce effectively. Industrial uses for process water and for cooling are likewise regulated by the water's temperature. Temperature, therefore, is an important physical parameter which to some extent regulates many of the beneficial uses of water. The Federal Water Pollution Control Administration in 1967 called temperature a

catalyst, a depressant, an activator, a restrictor, a stimulator, a controller, a killer, one of the most important and most influential water quality characteristics to life in water."

RATIONALE:

The suitability of water for total body immersion is greatly affected by temperature. In temperate climates, dangers from exposure to low temperatures is more prevalent than exposure to elevated water temperatures. Depending on the amount of activity by the swimmer, comfortable temperatures range from 20° C to 30° C. Short durations of lower and higher temperatures can be tolerated by most individuals. For example, for a 30-minute period, temperatures of 10° C or 35° C can be tolerated without harm by most individuals (NAS, 1974).

Temperature also affects the self-purification phenomenon in water bodies and therefore the aesthetic and sanitary qualities that exist. Increased temperatures accelerate the biodegradation of organic material both in the overlying water and in bottom deposits which makes increased demands on the dissolved oxygen resources of a given system. The typical situation is exacerbated by the fact that oxygen becomes less soluble as water temperature increases. Thus, greater demands are exerted on an increasingly scarce resource which may lead to total oxygen depletion and obnoxious septic conditions. These effects have been described by Phelps (1944), Carp (1963), and Velz (1970).

Indicator enteric bacteria, and presumably enteric pathogens, are likewise affected by temperature. It has been shown that both total and fecal coliform bacteria die away more rapidly in the environment with increasing temperatures (Ballentine and

Kittrell, 1968).

Temperature effects have been shown for water treatment processes. Lower temperatures reduce the effectiveness of coagulation with alum and subsequent rapid sand filtration. In one study, difficulty was especially pronounced below 5° C (Hannah, et al., 1967). Decreased temperature also decreases the effectiveness of chlorination. Based on studies relating chlorine dosage to temperature, and with a 30-minute contact time, dosages required for equivalent disinfective effect increased by as much as a factor of 3 when temperatures were decreased from 20° C to 10° C (Reid and Carlson, 1974). Increased temperature may increase the odor of water because of the increased volatility of odor-causing compounds (Bumson, 1938). Odor problems associated with plankton may also be aggravated.

The effects of temperature on aquatic organisms have been the subject of comprehensive literature reviews (Brett, 1956; Fry, 1967; FWPCA, 1967; Kine, 1970) and annual literature reviews published by the Water Pollution Control Federation (Coutant, 1968, 1969, 1970, 1971; Coutant and Goodyear, 1972; Coutant and Pfuderer, 1973, 1974). Only highlights from the thermal effects on aquatic life are presented here.

Temperature changes in water bodies can alter the existing aquatic community. The dominance of various phytoplankton groups in specific temperature ranges has been shown. For example, from 20° C to 25° C, diatoms predominated; green algae predominated from 30° C; to 35° C and blue-greens predominated above 35° C

(Cairns, 1956). Likewise, changes from a coldwater fishery to a warm-water fishery can occur because temperature may be directly lethal to adults or fry cause a reduction of activity or limit reproduction (Brett, 1960).

Upper and lower limits for temperature have been established for many aquatic organisms. Considerably more data exist for upper as opposed to lower limits. Tabulations of lethal temperatures for fish and other organisms are available (Jones, 1964; FWPCA, 1967 NAS, 1974). Factors such as diet, activity, age, general health, osmotic stress, and even weather contribute to the lethality of temperature. The aquatic species, thermal accumulation state and exposure time are considered the critical factors (Parker and Krenkel, 1969).

The effects of sublethal temperatures on metabolism, respiration, behavior, distribution and migration, feeding rate, growth, and reproduction have been summarized by De Sylva (1969). Another study has illustrated that inside the tolerance zone there is encompassed a more restrictive temperature range in which normal activity and growth occur and yet an even more restrictive zone inside that in which normal reproduction will occur (Brett, 1960).

De Sylva (1969) has summarized available data on the combined effects of increased temperature and toxic materials on fish indicate that toxicity generally increases with increased temperature and that organisms subjected to stress from toxic materials are less tolerant of temperature extremes.

The tolerance of organisms to extremes of temperature is a function of their genetic ability to adapt to thermal changes

within their characteristic temperature range, the acclimation temperature prior to exposure, and the time of exposure to the elevated temperature (Coutant, 1972). The upper incipient lethal temperature or the highest temperature that 50 percent of a sample of organisms can survive is determined on the organism at the highest sustainable acclimation temperature. The lowest temperature that 50 percent of the warm acclimated organisms can survive in is the ultimate lower incipient lethal temperature. True acclimation to changing temperatures requires several days (Brett, 1941). The lower end of the temperature accommodation range for aquatic life is 0° C in fresh water and somewhat less for saline waters. However, organisms acclimated to relatively warm water, when subjected to reduced temperatures that under other conditions of acclimation would not be detrimental, may suffer a significant mortality caused by thermal shock (Coutant, 1972).

Through the natural changes in climatic conditions, the temperatures of water bodies fluctuate daily, as well as seasonally. These changes do not eliminate indigenous aquatic populations, but affect the existing community structure and the geographic distribution of species. Such temperature changes are necessary to induce the reproductive cycles of aquatic organisms and to regulate other life factors (Mount, 1969).

Artificially induced changes such as the return of cooling water or the release of cool hypolimnetic waters from impoundments may alter indigenous aquatic ecosystems (Coutant, 1972). Entrained organisms may be damaged by temperature

increases across cooling water condensers if the increase is sufficiently great or the exposure period sufficiently long. Impingement upon condenser screens, chlorination for slime control, or other physical insults damage aquatic life (Raney, 1969; Patrick, 1969 (b)). However, Patrick (1969(a)) has shown that algae passing through condensers are not injured if the temperature of the outflowing water does not exceed 345° C.

In open waters elevated temperatures may affect periphyton, benthic invertebrates, and fish, in addition to causing shifts in algal dominance. Trembley (1960) studies of the Delaware River downstream from a power plant concluded that the periphyton population was considerably altered by the discharge.

The number and distribution of bottom organisms decrease as water temperatures increase. The upper tolerance limit for a balanced benthic population structure is approximately 32° C. A large number of these invertebrate species are able to tolerate higher temperatures than those required for reproduction (FWPCA, 1967).

In order to define criteria for fresh waters, Coutant (1972) cited the following as currently definable requirements:

1. Maximum sustained temperatures that are consistent with maintaining desirable levels of productivity,
2. maximum levels of metabolic acclimation to warm temperatures that will permit return to ambient winter temperatures should artificial sources of heat cease,
3. Time-dependent temperature limitations for survival of brief exposures to temperature extremes, both upper and lower,

4. Restricted temperature ranges for various states of reproduction, including (for fish) gametogenesis, spawning migration, release of gametes, development of the embryo, commencement of independent feeding (and other activities) by juveniles, and temperatures required for metamorphosis, emergence, or other activities of lower forms,

5. Thermal limits for diverse species compositions of aquatic communities, particularly where reduction in diversity creates nuisance growths of certain organisms, or where important food sources (food chains) are altered,

6. Thermal requirements of downstream aquatic life (in rivers) where upstream diminution of a coldwater resource will adversely affect downstream temperature requirements.

The major portion of such information that is available, however, is for freshwater fish species rather than lower forms of marine aquatic life.

The temperature-time duration for short-term exposures such that 50 percent of a given population will survive an extreme temperature frequently is expressed mathematically by fitting experimental data with a straight line on a semi-logarithmic plot with time on the logarithmic scale and temperature on the linear scale (see fig. 1). In equation form this 50 percent mortality relationship is:

$$\log^{10} (\text{time (minutes)}) = a + b (\text{Temperature } (^{\circ} \text{C}))$$

where: \log^{10} = logarithm to base 10 (common logarithm)

a = intercept on the "y" or logarithmic axis of the line fitted to experimental data and which is available for some species from Appendix II-C, of the National Academy of Sciences document.

b = slope of the line fitted to experimental data and which is available for some species from Appendix II-C, of the National Academy of Sciences document.

To provide a safety factor so that none or only a few organisms will perish, it has been found experimentally that a

criterion of 2° C below maximum temperature is usually sufficient (Black, 1953). To provide safety for all the organisms, the temperature causing a median mortality for 50 percent of the population would be calculated and reduced by 2° C in the case of an elevated temperature. Available scientific information includes upper and lower incipient lethal temperatures, coefficients "a" and "b" for the thermal resistance equation, and information of size, life stage, and geographic source of the particular test species (Appendix II-C, NAS, 1974).

Maximum temperatures for an extensive exposure (e.g., more than 1 week) must be divided into those for warmer periods and winter. Other than for reproduction, the most temperature-sensitive life function appears to be growth (Coutant, 1972). Coutant (1972) has suggested that a satisfactory estimate of a limiting maximum weekly mean temperature may be an average of the optimum temperature for growth and the temperature for zero net growth.

Because of the difficulty in determining the temperature of zero net growth, essentially the same temperature can be derived by adding to the optimum essentially to temperature (for growth or other physiological functions) a factor calculated as one-third of the difference between the ultimate upper incipient lethal temperature and the optimum temperature (NAS, 1974). In equation form:

$$\begin{array}{l} \text{Maximum weekly} \\ \text{average} = \\ \text{temperature} \end{array} = \begin{array}{l} \text{optimum} + \frac{1}{3} \\ \text{temperature} \end{array} \begin{array}{l} \text{(ultimate upper} \\ \text{incipient lethal} \\ \text{temperature)} \end{array} \begin{array}{l} \text{optimum} \\ \text{temperature} \\ \text{(temperature)} \end{array}$$

Since temperature tolerance varies with various states of development of a particular species, the criterion for a

particular location would be calculated for the most important life form likely to be present during a particular month. One caveat in using the maximum weekly mean temperature is that the limit for short-term exposure must not be exceeded. Example calculations for predicting the summer maximum temperatures for short-term survival and for extensive exposure for various fish species are presented in Table 11. These calculations use the above equations and data from EPA's Environmental Research Laboratory in Duluth.

The winter maximum temperature must not exceed the ambient water temperature by more than the amount of change a specimen acclimated to the plume temperature can tolerate. Such a change could occur by a cessation of the source of heat or by the specimen being driven from an area by addition of biocides or other factors. However, there are inadequate data to estimate a safety factor for the "no stress" level from cold shocks (NAS, 1974). Figure 2 was developed from available data in the literature (ERL-Duluth, 1976) and can be used for estimating allowable winter temperature increases.

Coutant (1972) has reviewed the effects of temperature on aquatic life reproduction and development. Reproductive events are noted as perhaps the most thermally restricted of all life phases assuming other factors are at or near optimum levels. Natural short-term temperature fluctuations appear to cause reduced reproduction of fish and invertebrates.

TABLE 11.-Example Calculated Values for
Maximum Weekly Average Temperatures for Growth and Short-Term
Maxima for Survival for Juveniles and
Adults During the Summer
(Centigrade and Fahrenheit).

Species	Growth ^a		Maxima ^b	
Atlantic salmon	20	(68)	23	(73)
Bigmouth buffalo				
Black crappie	27	(81)		
Bluegill	32	(90)	35	(95)
Brook trout	19	(66)	24	(75)
Carp				
Channel catfish	32	(90)	35	(95)
Coho salmon	18	(64)	24	(75)
Emerald shiner	30	(86)		
Freshwater drum				
Lake herring (Cisco)	17	(63)	25	(77)
Largemouth bass	32	(90)	34	(93)
Northern pike	28	(82)	30	(86)
Rainbow trout	19	(66)	24	(75)
Sauger	25	(77)		
Smallmouth bass	29	(84)		
Smallmouth buffalo				
Sockeye salmon	18	(64)	22	(72)
Striped bass				
Threadfin shad				
White bass				
White crappie	28	(82)		
White sucker	28	(82)		
Yellow perch	29	(84)		

a - Calculated according to the equation (using optimum temperature for growth)

maximum weekly average temperature for growth = optimum temperature + 1/3 (ultimate incipient lethal temperature - optimum temperature).

b - Based on temperature ($^{\circ}\text{C}$) = $1/b (\log^{10} \text{time}_{(\text{min.})} - a)$
 2°C , acclimation at the maximum weekly average temperature for summer growth, and data in Appendix II-C of Water Quality Criteria, published by National Academy of Sciences.

c - Based on data for larvae (ERL-Duluth, 1976).

There are inadequate data available quantitating the most temperature-sensitive life stages among various aquatic species. Uniform elevation of temperature a few degrees but still within the spawning range may lead to advanced spawning for spring spawning species and delays for fall spawners. Such changes may not be detrimental unless asynchrony occurs between newly hatched juveniles and their normal food source. Such asynchrony may be most pronounced among anadromous species or other migrants who pass from the warmed area to a normally chilled, unproductive area. Reported temperature data on maximum temperatures for spawning and embryo survival have been summarized in Table 12 (from ERL-Duluth 1976).

Although the limiting effects of thermal addition to estuarine and marine waters are not as conspicuous in the fall, winter, and spring as during the summer season of maximum heat stress, nonetheless crucial thermal limitations do exist. Hence, it is important that the thermal additions to the receiving waters be minimized during all seasons of the year. Size of harvestable stocks of commercial fish and shellfish, particularly near geographic limits of the fishery, appear to be markedly influenced by slight changes in the long-term temperature regime (Dow, 1973).

Jefferies and Johnson (1974) studied the relationship between temperature and annual variation in 7-year catch data for winter flounder, Pseudopleuronectes americanus, in Narragansett Bay, Rhode Island, revealed that a 78 percent decrease in annual catch correlated closely with a 0.5°C increase in the average

temperature over the 30-month period between spawning and recruitment into the fishery. Sissenwine's 1974 model predicts a 68 percent reduction of recruitment in yellowtail flounder, Limanda ferruginea, with a 1°C long-term elevation in southern New England waters.

TABLE 12.

Summary of Reported Values for
Maximum Weekly Average Temperature for Spawning and Short-Term
Maxima for Embryo Survival During the Spawning Season
(Centigrade and Fahrenheit)

Species	Spawning _a		Embryo Survival _b	
	°C	(°F)	°C	(°F)
Atlantic Salmon	5	(41)	7	(45)
Bigmouth Buffalo	17	(63)	27	(81) ^c
Black Crappie				
Bluegill	25	(77)	34	(93)
Brook Trout	9	(48)	13	(55)
Carp	21	(70)	33	(91)
Channel Catfish	27	(81)	29	(84)
Coho Salmon	10	(50)	13	(55)
Emerald Shiner	24	(75)	28	(82) ^c
Freshwater Drum	21	(70)	26	(79)
Lake Herring (Cisco)	3	(37)	8	(46)
Largemouth Bass	21	(70)	27	(81)
Northern Pike	11	(52)	19	(66)
Rainbow Trout	9	(48)	13	(55)
Sauger	10	(50)	21	(70)
Smallmouth Bass	17	(63)		
Smallmouth Buffalo	17	(63)	21	(70)
Sockeye Salmon	10	(50)	13	(55)
Striped Bass	18	(64)	24	(75)
Threadfin Shad	18	(64)	34	(93)
White Bass	17	(63)	26	(79)
White Crappie	18	(64)	23	(73)
White Sucker	10	(50)	20	(68)
Yellow Perch	12	(54)	20	(68)

- a - the optimum or mean of the range of spawning temperatures reported for the species (ERL-Duluth, 1976).
- b - the upper temperature for successful incubation and hatching reported for the species (ERL-Duluth, 1976).
- c - upper temperature for spawning.

Community balance can be influenced strongly by such temperature-dependent factors as rates of reproduction, recruitment, and growth of each component population. A few degrees elevation in average monthly temperature can appreciably alter a community through changes in interspecies relationships. A 50 percent reduction in the softshell clam fishery in Maine by the green crab, Carcinus maenus, illustrates how an increase in winter temperatures can establish new predator-prey relationships. Over a period of 4 years, there was a natural amelioration of temperature and the monthly mean for the coldest month of each year did not fall below 2°C. This apparently precluded appreciable ice formation and winter cold kill of the green crab and permitted a major expansion of its population, with increased predation of the softshell clam resulting (Glude, 1954; Welch, 1968).

Temperature is a primary factor controlling reproduction and can influence many events of the reproductive cycle from gametogenesis to spawning. Among marine invertebrates, initiation of reproduction (gametogenesis) is often triggered during late winter by attainment of a minimum environmental threshold temperature. In some species, availability of adequate food is also a requisite (Pearse, 1970; Sastry, 1975; deVlaming, 1971). Elevated temperature can limit gametogenesis by preventing accumulation of nutrients in the gonads. This problem could be acute during the winter if food availability and feeding activity is reduced. Most marine organisms spawn during the spring and summer; gametogenesis is usually initiated during the

previous fall. It should also be noted that some species spawn only during the fall (herring), while others during the winter and very early spring. At the higher latitudes, winter breeders include such estuarine community dominants as acorn barnacles, Balanus balanus and B. balanoides, the edible blue mussel Mytilus edulis, sea urchin, Strongylocentrotus drobachiensis, sculpin, and the winter flounder, Pseudopleuronectes americanus. The two boreal barnacles require temperatures below 10°C before egg production will be initiated (Crisp, 1957). It is clear that adaptations for reproduction exist which are dependent on temperature conditions close to the natural cycle.

Juvenile and adult fish usually thermoregulate behaviorally by moving to water having temperatures closest to their thermal preference. This provides a thermal environment which approximates the optimal temperature for many physiological functions, including growth (Neill and Magnuson, 1974). As a consequence, fishes usually are attracted to heated water during the fall, winter, and spring. Avoidance will occur as warmer temperature exceeds the preferendum by 1 to 3°C (Coutant, 1975). This response precludes problems of heat stress for juvenile and adult fishes during the summer, but several potential problems exist during the other seasons. The possibility of cold shock and death of plume-entrained fish resulting from winter plant shutdown is well recognized. Also, increased incidence of disease and a deterioration of physiological condition has been observed among plume-entrained fishes, perhaps because of insufficient food (Massengill, 1973). A weight loss of approximately 10 percent for each 1°C rise in water temperature

has been observed in fish when food is absent. (Phillips et al., 1960) There may also be indirect adverse effects on the indigenous community because of increased predation pressure if thermal addition leads to a concentration of fish which are dependent on this community for their food.

Fish migration is often linked to natural environmental temperature cycles. In early spring, fish employ temperature as their environmental cue to migrate northward (e.g., menhaden, bluefish) or to move inshore (winter flounder). Likewise, water temperature strongly influences timing of spawning runs of anadromous fish into rivers (Leggett and Whitney, 1972). In the autumn, a number of juvenile marine fishes and shrimp are dependent on a drop in temperature to trigger their migration from estuarine nursery grounds for oceanic dispersal or southward migration (Lund and Maltezos, 1970; Talbot, 1966).

Thermal discharges should not alter diurnal and tidal temperature variations normally experienced by marine communities. Laboratory studies show thermal tolerance to be enhanced when animals are maintained under a diurnally fluctuating temperature regime rather than at a constant temperature (Costlow and Bookhout, 1971; Furch, 1972; Hoss, et al.,). A daily cyclic regime can be protective additionally as it reduces duration of exposure to extreme temperatures (Pearce, 1969; Gonzalez, 1972).

Summer thermal maxima should be established to protect the various marine communities within each biogeographic region. During the summer, naturally elevated temperatures may be of

sufficient magnitude to cause death or emigration (Glynn, 1968; Vaughn, 1961). This more commonly occurs in tropical and warm temperate zone waters, but has been reported for enclosed bays and shallow waters in other regions as well (Nichols, 1918). Summer heat stress also can contribute to increased incidence of disease or parasitism (Sinderman, 1965); reduce or block sexual maturation (Thorhaug, et al., 1971; deVlaming, 1972); inhibit or block embryonic cleavage of larval development (Calabrese, 1969); reduce feeding and growth of juveniles and adults (Olla and Studholme, 1971); result in increased predation (Gonzalez, 1972); and reduce productivity of macroalgae and seagrasses (South and Hill, 1970; Zieman, 1970). The general ceilings set forth here are derived from studies delineating limiting temperatures for the more thermally sensitive species or communities of a biogeographic region.

Thermal effects data are presently insufficient to set general temperature limits for all coastal biogeographic regions. The data enumerated in the Appendix, plus any additional data subsequently generated, should be used to develop thermal limits which specifically consider communities relevant to given water bodies.

(QUALITY CRITERIA FOR WATER, JULY 1976) PB-263943
SEE APPENDIX C FOR METHODOLOGY